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ORIGINAL ARTICLE

Performance enhancement of magnetic levitation system using teaching learning based optimization

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Abstract This paper demonstrates the potency of evolution based optimization techniques in the sense of enhancing the system's performance. Teaching Learning Based Optimization (TLBO) is a well-known evolutionary algorithm used to optimize the parameters of the PID controller so as to improve the performance of the magnetic levitation system. The TLBO search algorithm is split into two phases, the teacher phase and the learner phase. The teacher phase is comprised of having minimum performance index as compared to learner phase. The learners improve their knowledge on the basis of teacher's performance. The parameters are tuned while minimizing the performance index of the system. The performance index incorporated in this paper is the integral time weighted square error (ITSE). The corroboration of the above technique is ended by comparing it with the conventional control techniques.
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1. Introduction

Now a days, PID controller is being readily used due to having capability of improving their parameters with both the tuning approaches i.e., the conventional and the heuristic. The PID controller is well-known in the process control industry and in fact is well suited for any type of linear time-invariant system [1].

The exquisiteness of this technique is its intelligibility, easy execution and potential to control closed-loop stable system. The problem linked up with the PID controller is the tuning of the three parameters i.e. the proportional gain, the integral gain and the derivative gain. Initially the parameters were tuned by the conventional methods like trial & error, Ziegler-Nichols (Z-N), Cohen-Coon and others [2]. The Z-N method received the most attention due to having ability of providing the best starting solution but sometimes fail to meet the design requirements and in fact unable to provides the global optimum solution. With the emergence of optimization techniques like genetic algorithm (GA), particle swarm optimization (PSO), ant colony system (ACO), bacterial foraging (BF) etc., pushed back the conventional techniques and played a vital role for the improvement of the PID controller in terms of tuning their parameters [3].

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In this paper, a nature-inspired algorithm known as TLBO is applied for the improvement of the PID controller [4]. The difference between other algorithms and the TLBO is that it does not require any algorithm parameters like population size, crossover rate, mutation rate in GA and inertia weight, social & cognitive parameters in case of PSO.

The outcome of TLBO algorithm is dependent on the growth of the learners with the potential strength of the teacher. The outcome is related to the performance of the learners as well as the teacher. In this algorithm, learners upgrade their knowledge on the basis of the teacher knowledge. In fact teacher is recognized as a highly qualified person. The teaching behavior directly influenced the learner's grades i.e. if the teacher teaches the student in a well mannered way then the outcome of the students will definitely improve.

The TLBO algorithm is proposed by Rao et al. in 2010 to optimize the constrained and unconstrained function with less computational efforts and high consistency [5–7]. The algorithm works on the principle of preserving the fittest person as the teacher and improvises the other functions on the basis of best solution obtained [8,9]. Here, the effectiveness of the TLBO algorithm is checked by levitating the metal ball in the air space while controlling the electromagnetic force via PID controller.

Magnetic levitation system is considered as a perfect test-bed benchmark problem for control engineers. It has been very popular because of having similar working principle like the magnetic levitation trains. It is widely used in magnetic bearings, wind tunnel models, vibration isolation of sensitive machinery etc. The magnetic levitation system is inherently unstable with one of the system's zero or pole lies in the right-half of the s-plane (RHP). The system having pole in the RHP is unstable non-minimum phase system and the system having zero in the RHP is stable nonminimum phase system.

The organization of this paper is as follows. In Section 2, brief description of magnetic levitation system. Section 3 describes the PID control strategy. Section 4 presents the description of TLBO algorithm with simulation results and comparison with conventional method. Section 5 covers the simulation results and discussion. Finally, the conclusion is shown in Section 6 and the references.

2. Magnetic levitation system

The magnetic levitation system is highly unstable system consists of an electromagnet coil mounted on top of the box, infrared sensor to sense the position of the metal ball [10]. The vertical and the horizontal movement of the ball are split by the infra-red sensor. The electromagnetic force is varying in such a way so that the metal ball can move in the air space in between 0.25 cm to 0.5 cm. The distance is measured from the electromagnetic coil, if the metal ball can cross this specified distance then there are chances of being fallen down or it attracts on outer surface of the coil [11–14]. The electromagnetic force is contradictory to the gravitational force g and sustains the metal ball in a levitated position. The electromagnetic force F depends on the electromagnetic current I, and the air gap X between the metal ball and the electromagnet coil [15–17]. The movement of the metal ball in the air space is given by

$$F = Mg - K_m\left(\frac{i_m}{x_b}\right)^2 \tag{1}$$

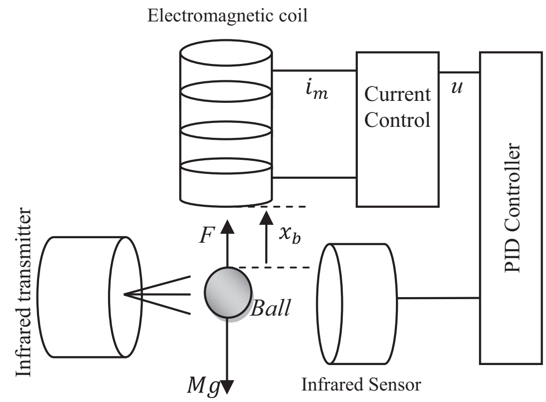

Fig. 1 Magnetic levitation system.

where i_m is the current in electromagnetic coil (Ampere), x_b is the distance of the ball from the electromagnetic coil (m), g is the gravitational constant (m/s^2), K_m is the magnetic force constant of electromagnet and ball pair, M is the mass of the metal ball (kg). Fig. 1 shows the schematic diagram of the magnetic levitation system.

Newton's second law of motion is used to derive the differential equation of the magnetic levitation system given by

$$M\frac{d^2x_b}{dt^2} = Mg - K_m\left(\frac{i_m}{x_b}\right)^2 \tag{2}$$

The value of coil current and the position of the metal ball at the operating point can be derived by putting $\frac{d^2x_b}{dt^2} = 0$ in Eq. (2) gives

$$x_{b_{ss}} = \sqrt{\frac{K_m}{Mg}}i_{m_{ss}} \tag{3}$$

where $x_{b_{ss}}$ and $i_{m_{ss}}$ are the value of position of metal and current of electromagnetic coil at the operating point. This coil current is sufficient in theoretical sense to levitate the position of the metal ball to the desired location but it fails practically due to variation at operating point because of external disturbances, parameter uncertainties and others. Therefore, there is a requirement of an efficient controller which is capable of handling such irregularities of the system. The magnetic levitation system is linearized by taking the approximates of x_b and i_m as

$$x_b(t) \triangleq \hat{x}_b + x_{b_{ss}} \tag{4}$$

$$i_m(t) \triangleq \hat{i}_m + i_{m_{ss}} \tag{5}$$

where $\hat{x}_b$ and $\hat{i}_m$ are the variations of metal ball position and coil current around the operating point. Thus the dynamic equation of the magnetic levitation system can be written as

$$M\frac{d^2\hat{x}_b}{dt^2} = Mg - K_m\left(\frac{\hat{i}_m + i_{m_{ss}}}{\hat{x}_b + x_{b_{ss}}}\right)^2 \tag{6}$$

Now, linearizing the above system using Taylor's series expansion method and assuming that $\hat{x}_b \gg x_{b_{ss}}$, $\hat{i}_m \gg i_{m_{ss}}$

$$\frac{d^2\hat{x}_b}{dt^2} = \frac{1}{M}\left\{\frac{\partial}{\partial\hat{x}_b}\left(Mg - K_m\left(\frac{\hat{i}_m + i_{m_{ss}}}{\hat{x}_b + x_{b_{ss}}}\right)^2\right)\Bigg|_{\hat{x}_b=0,\hat{i}_m=0}\right.$$

$$\left.\hat{x}_b + \frac{\partial}{\partial\hat{i}_m}\left(Mg - K_m\left(\frac{\hat{i}_m + i_{m_{ss}}}{\hat{x}_b + x_{b_{ss}}}\right)^2\right)\Bigg|_{\hat{x}_b=0,\hat{i}_m=0}\hat{i}_m\right\} \tag{7}$$

Therefore,

$$\frac{d^2\hat{x}_b}{dt^2} = \frac{1}{M}\left(\frac{2K_m i^2_{m_{ss}}}{x^3_{b_{ss}}}\hat{x}_b - \frac{2K_m i_{m_{ss}}}{x^2_{b_{ss}}}\hat{i}_m\right) \tag{8}$$

By taking Laplace transform the transfer function of the magnetic levitation system is given as

$$G(s) = \frac{\widehat{X}_b(s)}{\widehat{I}_m(s)} = -\frac{K_2}{s^2 - K_1} \tag{9}$$

where $K_1 = \frac{2K_m i^2_{m_{ss}}}{Mx^3_{b_{ss}}}$ and $K_2 = \frac{2K_m i_{m_{ss}}}{Mx^2_{b_{ss}}}$ with $M = 0.002kg$, $g = 9.81m/sec^2$. The equilibrium point of the feedback make magnetic levitation system is $[x_{b_{ss}} = -1.5V, i_{m_{ss}} = 0.8A]$. Therefore, the transfer function of the magnetic levitation system is given by

$$G(s) = \frac{-24.5250}{s^2 + 13.08} \tag{10}$$

The open-loop response of the magnetic levitation system is shown in Fig. 2. The open-loop poles of the system are located on the imaginary axis i.e. at $s = \pm j3.6166$ and therefore the system lead to instability or having sustained oscillations. The complexity associated with this system is that the closed-loop system is unstable with one of the system pole lying in the right-half of the s-plane. The closed-loop poles are located at $s = \pm 3.3823$. Therefore, there is a requirement of an efficient controller which can effectively stabilize the position of the metal ball so that it can levitate in the air space.

3. PID controller

PID controller is known as the proportional, integral and derivative controller. It is very popular in the control system society because of its controlling capability. There are various combination of PID controller like PI, PD, PID-D, I-PD and many more depending on the system requirements. Each term has its own role i.e. proportional controller is used to increase the loop gain of the system, thereby reducing its sensitivity to plant parameter variations. The integral controller increases the order of the system and reduces the steady-state error of the system by adding a pole at the origin of the -plane. The derivative controller tends to stabilize the system by introducing derivative of the error.

The values of parameters of the PID controller can also be determined by trial & error method if the values of the open-loop transfer function are not exactly known. If the parameters of the plant are subject to large variations, the gain constants can be adjusted to improve the system performance. The transfer function of the PID controller is given by

$$\mathrm{U(s)} = \left(\mathrm{K_p} + \mathrm{K_i}\frac{1}{\mathrm{s}} + \mathrm{K_d s}\right)\mathrm{E(s)} \tag{11}$$

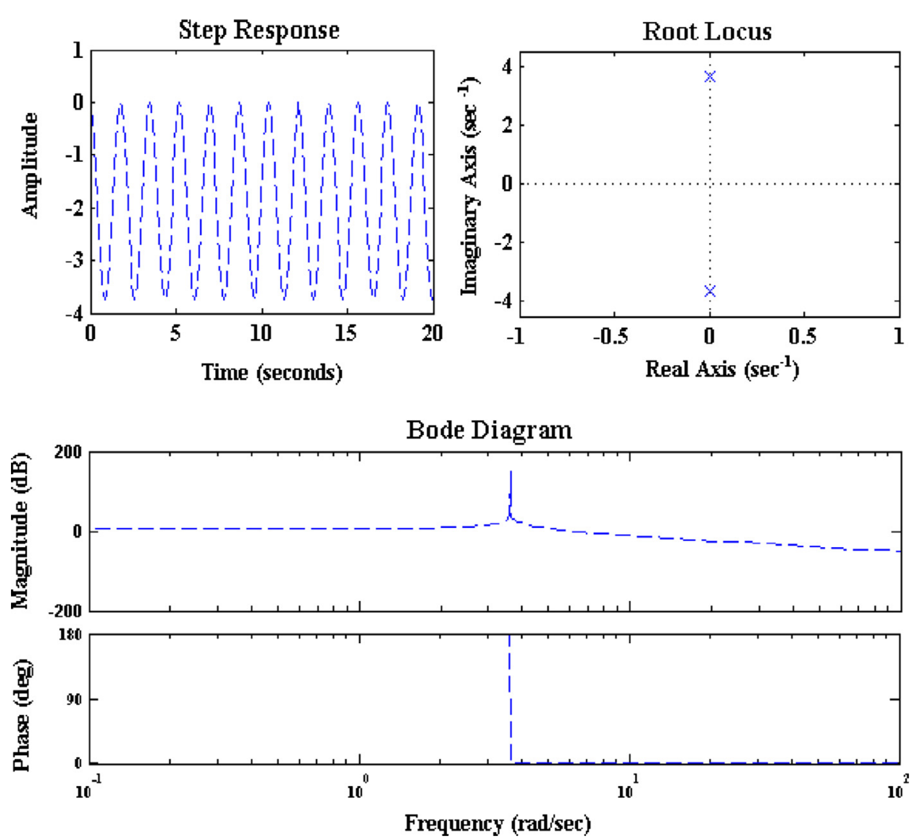

Fig. 2 Open-loop response of magnetic levitation system.

where K_pE is the proportional to the error, K_iE/s is proportional to the integral of the error, K_dsE is proportional to the derivative of the error, and U is controller output. To find out the starting point of the TLBO algorithm, the parameters of PID controller are tuned using trial & error method (*pid* tool of MATLAB) because the conventional tuning techniques like Ziegler-Nichols, Cohen-Coon and approximated MIGO method are fails to give the approximate starting solution for the PID controller. Though, these techniques would consider being the best conventional approach for finding the starting solution for the PID controller. The controller is designed for magnetic levitation system given in Eq. (10) in such a way so that it meets the following design requirements:

- Settling Time $(t_s) \leqslant 1$ s.
- Percentage Overshoot $(M_p) \leqslant 10$
- Gain Margin (GM) $\geqslant 6$ dB
- Phase Margin (PM) $\geqslant 60^0$

The parameters of the PID controller tuned using trial and error (T&E) method are given in Table 1, closed-loop responses like step response, bode plot are shown in Figs. 3 and 4. The time-domain characteristics like rise time, settling time, percentage overshoot, peak time and frequency-domain specifications like gain margin, phase margin are given in Table 2.

The performance characteristic shows that the controller successfully meets the settling time requirement but it fails to accomplish the percentage overshoot of the system. All Eigen-values of the closed-loop system are lying in the left-half of the s-plane which proves that the system is stable. The infinite gain margin shows that the system remains stable with any value of gain K where K is the feed-forward gain of the closed-loop system varies from 0 to ∞. The drawback of the PID controller tuned using T&E method is that it is unable to meet the phase margin requirement. In order to improve the performance of the system the parameters of the PID controller needs modification. The modification can be performed by updating the parameters using meta-heuristic approach. The meta-heuristic techniques searches for the optimum solution while minimizing the objective function i.e. the performance index of the system.

4. Description of TLBO algorithm

The main concept of teaching learning based optimization is the replication of a class teaching methodology for the search of optimum solution. The algorithm works into two successive phases; the "teacher phase" and the "learner phase". During the teacher phase the teacher teaches the students on the basis of his/her knowledge. If a teacher is more knowledgeable and has influence in the class then there are chances of improving the knowledge of the students/learners. It is not possible that all the learners grasp entire teaching material which the teacher taught them. The quality of learners can be judged from the grades they obtained. If the mean of the learners are decreasing then it is required that the teacher changes the teaching pattern. Only few of them can understand the whole material and such students may consider as a best student and are allow to share his/her valuable thoughts with other learners. The second phase is the learner phase in which the best student (based on his grades) act as a teacher for other learners. Therefore, the learners were allowed to interact with the acting teacher to clear his/her doubts for the improvement of their knowledge in the respective subject. The subjects are the parameters for the PID controller and the teacher/learner with maximum marks or minimum performance index are treated as the near optimum solution for the PID controller. The overall block diagram of the magnetic levitation system combined with the TLBO algorithm is shown in Fig. 5. The convergence of the TLBO algorithm on the way to global optimum solution is supervised by the performance index of the system. As the iteration increased, the parameters of the PID controller are

Table 1 Parameters of PID controller tuned using trial & error method.

K_p	K_i	K_d
−20.4793	−9.2557	−0.71604

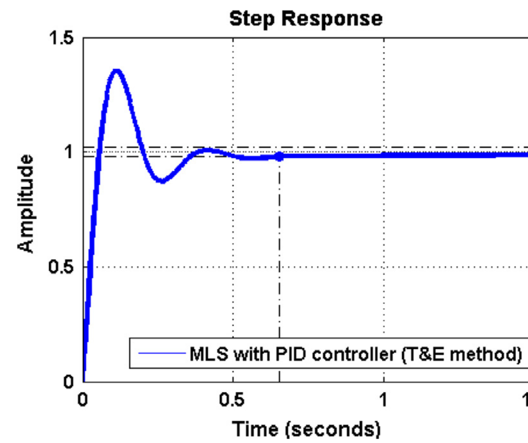

Fig. 3 Step response of MLS with PID controller tuned using T&E method.

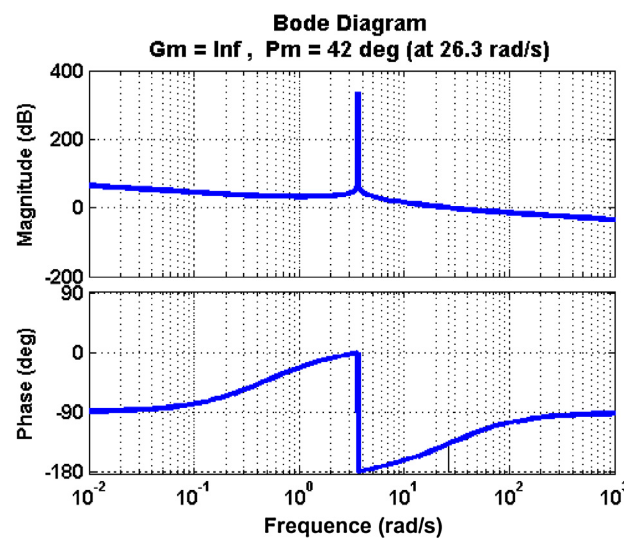

Fig. 4 Bode diagram of magnetic levitation system.

Table 2 Performance characteristics of magnetic levitation system with PID controller.

Rise time	Settling time	Percentage overshoot	Peak time	Gain margin	Phase margin
0.0443	0.656	35.5322	0.1130	Inf	42

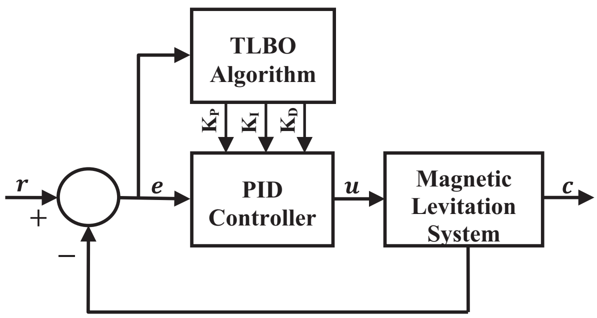

Fig. 5 Block diagram for optimum search using TLBO.

modified in such a way so that they produce minimum performance index.

The TLBO algorithm incorporates the following steps:

Step 1: Initialize the number of students i.e. generate the population. Evaluate the objective function of each student. The initial population is generated on the basis of parameters tuned using conventional method.

$$PID_n = [K_p \quad K_i \quad K_d]_n \tag{12}$$

where n represents the total number of student in a class.

Step 2: Calculate the mean of each student. Here, performance index of the system is considered for calculating the mean of the generated population.

$$PID_{mean} = \frac{\sum_n ITSE}{n} \tag{13}$$

Step 3: Identify the best student on the basis of minimum performance index achieved

$$\mathrm{PID_{best}} = [\mathrm{K_p} \quad \mathrm{K_i} \quad \mathrm{K_d}]_{\mathrm{min.ITSE}} \tag{14}$$

and also calculate the teaching factor so that the best one of them would act as a teacher for the next iteration.

$$\mathrm{TF} = \frac{\sum_n \mathrm{ITSE} - \mathrm{n}}{\sum_n \mathrm{ISE} - \mathrm{min.(ITSE)}} \tag{15}$$

Step 4: Now marks of all the students are modified and updated according to the marks obtained by the acting teacher as

$$\mathrm{PID_{new}} = \mathrm{PID_{old}} + \mathrm{r}(\mathrm{PID_{best}} - \mathrm{TF} * \mathrm{PID_{mean}}) \tag{16}$$

The above equation restructured the marks of all students and updates their grade sheet on the basis of their present performance. For these updated set of variables the performance index is calculated and compared with the ITSE of old students. If new solution is better than the previous one then it is stored for next iteration otherwise it is rejected. Here r is the random variable lies between 0 and 1.

Step 5: Select any two variables randomly from PID_{new} and compare the performance index of each student with the performance index of these two variables. If PID_{newi} is better then PID_{newj}

$$\mathrm{PID_{new}} = \mathrm{PID_{old}} + \mathrm{r}(\mathrm{PID_{new\,i}} - \mathrm{PID_{new}}) \tag{17}$$

Else

$$\mathrm{PID_{new}} = \mathrm{PID_{old}} + \mathrm{r}(\mathrm{PID_{new\,j}} - \mathrm{PID_{new\,i}}) \tag{18}$$

Step 6: Save the updated marks of the students and compare their performance index with the existing one. Opt the new marks if they are better in the sense of ITSE otherwise continue with the previous solution for next iteration. Stop the process if all the design requirements are fulfilled or the maximum number of iteration is reached.

5. Simulation results and discussion

In this section, the parameters of the PID controller are tuned by using TLBO algorithm is discussed. Initially the parameters are randomly selected on the basis of the parameters tuned using trial & error method. For TLBO algorithm, eighteen students are selected and one of them who have minimum performance index would consider as teacher for the next iteration. The teacher updates the knowledge of other students and guided them to secure good marks in the form of minimum performance index, so that all the controller design requirements are fulfilled. The performance is calculated for every parameter and they were sorted accordingly. The performance index or objective function chosen here is the ITSE of the system given as:

$$J = \int_{t_1}^{t_2} t.e^2(t)dt \tag{19}$$

where e is the error of the system, t is the time period $(t_1, t_2 \in 0, 100)$. The TLBO algorithm required around hundred number of iteration to fine-tune the parameters of the PID controller. The tuned parameters of the PID controller are shown in Table 3.

The issue associated with the optimization techniques of being struck at local optima is resolve by calculating the error, time-domain and frequency-domain characteristics at each & every instants. Also, two students are selected randomly from the class and performance of every student is compared with them to ensure that every student benefited with knowledge of the teacher. This shows the exploration property of the TLBO algorithm. The step response of the best three performers is shown in Fig. 6. The best one of them is considered as a teacher and others are as learners. The parameters tuned via TLBO algorithm fulfils all the design requirements i.e. both the settling time and percentage overshoot of the system gets improved and is shown in Table 4. The Bode diagram is shown in Fig. 7. The gain margin of the best three performers is infinite which shows that the system is highly stable and can handle any value of gain.

Table 3 Parameters of Pid controller tuned using TLBO.

S.No.	Randomly selected Parameters K_p	K_i	K_d	Parameters tuned with TLBO K_p	K_i	K_d
1	−20.4	−9.25	−0.71	−184.8	−249.96	−9.60
2	−9.40	−19.8	−0.05	−181.7	−249.30	−9.79
3	−10.25	−15	−0.8	−154.6	−249.66	−12.5
4	−22	−30	−0.12	−174.6	−249.78	−10.9
5	−15.06	−8	−0.32	−187.1	−249.97	−10.4
6	−11	−12	−0.12	−188.1	−249.50	−10.2
7	−21	−27	−0.10	−174.1	−249.9	−10.9
8	−31	−15.5	−0.31	−185.2	−249.67	−10.8
9	−23	−19	−0.52	−190.3	−249.08	−10.8
10	−40	−30	−5.1	−185.6	−249.75	−11.3
11	−30	−28	−4.1	−185.8	−248.87	−10.7
12	−25	−12	−0.82	−207.3	−249.91	−10.9
13	−10.5	−14	−0.2	−203	−249.71	−10.9
14	−10.2	−15	−0.8	−176.2	−249.87	−12
15	−20	−30	−0.01	−185.6	−248.42	−10.7
16	−15.1	−8	−0.32	−186	−249.22	−11.3
17	−10.2	−12	−0.12	−194	−249.28	−11.2
18	−20	−27	−0.10	−39.7	−258.31	−11.1

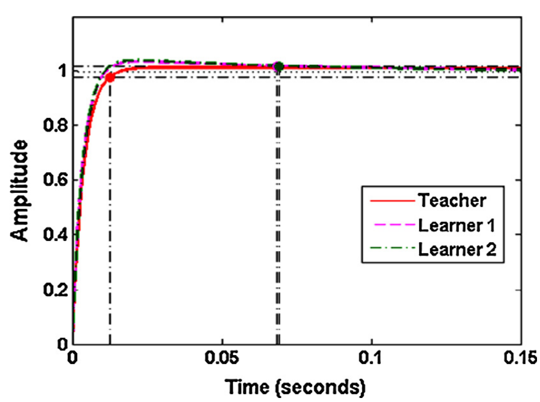

Fig. 6 Step response of magnetic levitation system with TLBO.

Table 4 Performance characteristics of TLBO algorithm.

	Teacher	Learner 1	Learner 2
Rise Time (seconds)	0.0077	0.0066	0.0065
Settling time (seconds)	0.012	0.068	0.069
Max. Overshoot (%)	1.28	3.53	4.00
Peak Time (seconds)	1.012	1.035	1.040
Gain Margin (dB)	∞	∞	∞
Phase Margin (degree)	170	163	161
ITSE	9.36×10^{-7}	9.39×10^{-7}	9.67×10^{-7}

The higher the phase margin the more stable is the system and for these tuned parameters, the phase margin is around 170^0. Some researcher given their theory on the phase margin that there are changes of getting sluggish response for larger phase margin but using TLBO algorithm the settling time

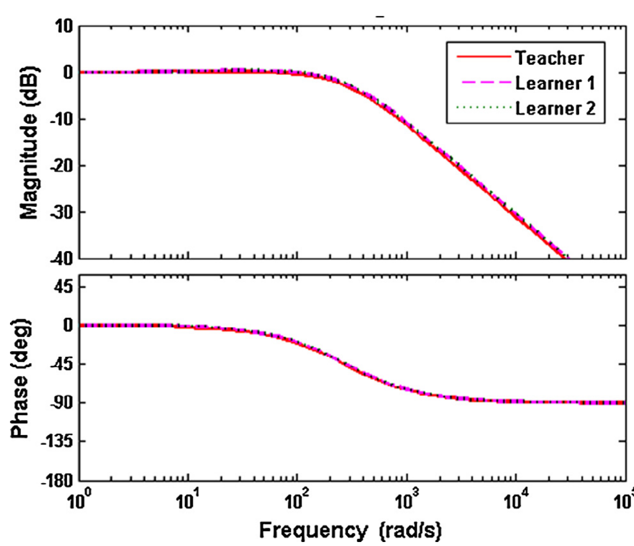

Fig. 7 Bode diagram of magnetic levitation system with TLBO.

and as well as peak overshoot of the system shows better response as compared to conventional techniques.

6. Conclusion

This paper discusses a new meta-heuristic technique known as teaching learning based optimization for controlling the position of the metal ball via magnetic levitation system. The parameters of the PID controller are tuned effectively by TLBO algorithm. The controller is used to levitate the position of the metal ball in the air-space by controlling the electromagnetic coil current. The coil current is controlled by sensing the position of the metal ball through infra-red sensor. The effectiveness of the proposed controller is validated by comparing it with the conventional tuning method. The simulation results performed in MATLAB shows that all the design requirements are successfully achieved. The TLBO technique ensures the improvement of the time domain and as well as the frequency domain specifications by minimizing the performance index of the system. The renowned properties like exploration and exploitation are handled appropriately by the TLBO algorithm. Though the TLBO algorithm fulfilled all the design requirements but still the tuning process is more iterative. Presently a new algorithm based on parameters-less Jaya algorithm proposed by Rao et al. is easier to implement as discussed in [18]. The algorithm moves towards the best solution while rejecting the worst solution. The author would like to apply such a simple and effective technique for the future work.

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